Canadian Association of Radiologists Journal 60 (2009) 19–34

CANADIAN ASSOCIATION OF RADIOLOGISTS JOURNAL

www.carjonline.org

Health Policy and Practice / Santé: politique et pratique médicale

Canadian Association of Radiologists: Consensus Guidelines and Standards for Cardiac CT

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Key Words: Coronary artery disease; Coronary artery calcium; Detection; Computed tomography angiography; CT; Coronary angiography; Multidetector CT; MDCT; CAR; Guidelines; Standards

Invasive coronary angiography remains the gold standard for imaging of the coronary arteries. Because of poor temporal and spatial resolution, noninvasive imaging of the heart using computed tomography (CT) had remained a challenge until the recent past. Since 1999, and the advent of 4-detector electrocardiogram (ECG)-gated CT, there have been rapid technical developments in CT technology and postprocessing tools, thus enabling an accurate noninvasive assessment of cardiac anatomy including the coronary arteries as well as cardiac function. Today, this relatively new technique increasingly is being requested and performed on a routine basis.

Although guidelines and standards for the performance of cardiac CT (CCT) have been published by other societies outside of Canada [1–5], the Canadian Association of Radiologists recognizes that Canadian radiologists play a leading and pivotal role in the safe and proper implementation of CCT throughout the country, as well as in the training and continuing medical education of physicians performing and interpreting CCT studies. This comprehensive article reviews the current evidence for CCT to date and outlines the standards for the implementation of a CCT program. Based on the review of the current literature and on expert opinion, recommendations regarding indications and contraindications for CCT also are provided.

Methods

The CCT expert committee comprises radiologists with cardiac expertise in each of the topic areas. Before completion, the standards and guidelines were distributed to the Canadian Association of Radiologists executive committee for the opportunity to provide feedback concerning the recommendations. The literature will be reviewed periodically and the standards and guidelines will be updated as new or compelling evidence is identified.

Literature Search Strategy

The literature was searched using MEDLINE (OVID: 1966 through October 2008), EMBASE OVID: (1988 through October 2008), and the Cochrane Library (OVID: issue 3, 2008). Reference lists of related articles and recent review articles also were scanned for additional citations.

Study Selection Criteria

Given the nature of the topic, it was widely accepted among the CCT Writing Group that the strength of the evidence from the published literature would vary considerably, and in many cases would not be sufficient to inform recommendations on the topic. In the event of limited data, it

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0846-5371/$ - see front matter
doi:10.1016/j.carj.2009.02.006

was agreed that expert consensus would be used to form the recommendations. As such, only the highest levels of evidence were considered such as systematic reviews, randomized controlled trials, meta-analyses, nonrandomized comparative studies, prospective single-cohort studies, and, finally, retrospective single-cohort studies. Articles were excluded from the systematic review of the evidence if they were reported in a language other than English or involved pediatric populations.

Results

Review of CCT Evidence

Calcium score

Coronary artery calcium (CAC) is a general surrogate for total atheroma burden [6]. Most of the studies that have addressed CAC have been based on results from electron-beam CT systems, which are largely no longer available. These systems have been replaced by multidetector CT (MDCT). Early studies have shown similar CAC scores can be obtained with these systems [7−9].

Outcome studies have shown that CAC scores add incremental prognostic value to the evaluation of asymptomatic patients at intermediate risk (10-year risk, 10%−20%) for a coronary event [10−15] in Caucasians using the Framingham risk score [16], the PROCAM score [17], or the European SCORE system [18]. The value of CAC scoring in asymptomatic patients at low risk or high risk of a coronary event is controversial [5,19]. There still are limited data concerning the predictive value of CAC in non-Caucasians.

CAC is not an indicator of significant coronary artery stenosis. Investigators have concluded that although CAC scores are highly sensitive, they are only moderately specific for the detection of a coronary artery stenosis greater than 50% [20].

A zero calcium score is associated with a very low event rate in most risk categories and is associated with a very low prevalence of ischemia on functional testing and significant coronary stenosis on invasive angiography [5,21].

There is significant variability in CAC scores on MDCT on sequential examinations [22,23].

Coronary Artery Imaging

Detection of coronary artery stenosis

Four- and 16-detector CT. Noninvasive CT imaging of the coronary arteries (CCTA) requires high temporal and spatial resolution and became possible with the development of MDCT technology.

The first generation of MDCT scanners were 4-slice systems. They were limited by long scan times, and lacked the temporal and spatial resolution of subsequent generations of scanners. The coronary arteries could be imaged but assessment was restricted to the proximal vessels and up to 25% of coronary segments were uninterpretable because of poor image quality [24,25].

The subsequent 16-slice scanners had improved temporal and spatial resolution and acquired data in a shorter breath-hold, resulting in improved imaging of the coronary tree. A recent meta-analysis of articles comparing cardiac CTA (CCTA) with conventional coronary angiography for the detection of coronary stenoses greater than 50% showed the following figures for 16-detector CT [26]. Per coronary segment analysis: sensitivity, 77%; specificity, 91%; positive predictive value, 60%; and negative predictive value, 96%. Per patient analysis: sensitivity, 95%; specificity, 69%; positive predictive value, 79%; and negative predictive value, 92%.

Despite the technical improvements with 16-detector CT, 4.4% of patients have nonevaluable scans and up to 29% (mean, 10%) of coronary segments remain unassessable [26]. Exclusion of these unassessable patients and segments from analysis in many articles gives a false impression of the diagnostic performance of MDCT and the earlier-described figures must be interpreted with this in mind.

Sixty-four−detector CT. At the time of this writing, the current generation of MDCT scanners are 64-detector technology. Having further improvements in spatial and temporal resolution and a shorter scan time, 64-detector CCTA allows significantly improved diagnostic performance over 16-detector technology [26−28]. Since the first publication on 64-detector CCTA in April 2005, [28] there has been a plethora of studies comparing 64-detector CCTA with conventional coronary angiography [29−41]. Five meta-analyses published over the past 2 years have had differing inclusion/exclusion criteria but confirm similar results, summarized in Tables 1 and 2 [26,27,42−44].

Per-segment sensitivity is 88% to 93%, specificity is 96% to 97%, positive predictive value is 73% to 79%, and negative predictive value is 96% to 99%. Per-patient sensitivity is 97% to 99%, specificity is 88% to 93%, positive predictive value is 93% to 94%, and negative predictive value is 95% to 100%. Nonevaluable scans occurred in 1.9% of patients and the 4% of segments were unevaluable [26].

The major advancements with 64-detector CCTA are a reduction in unevaluable scans and unevaluable vessel segments, and a considerable improvement in per-patient specificity and positive predictive value. Negative predictive

Table 1
Sixty-four−detector CCTA meta-analyses: per coronary segment analysis

	Sensitivity, %	Specificity, %	PPV, %	NPV, %
Vanhoenacker et al [27]	93	96	N/A	N/A
Hamon et al [26]	88	96	79	98
Sun et al [42]	90	96	75	98
Mowatt et al [43]	90	97	76	99
Stein et al [44]	90	96	73	96

N/A = not applicable; NPV = negative predictive value; PPV = positive predictive value.

Table 2
Sixty-four−detector CCTA meta-analyses: per-patient analysis

	Sensitivity, %	Specificity, %	PPV, %	NPV, %
Vanhoenacker et al [27]	99	93	N/A	N/A
Hamon et al [26]	97	90	93	96
Sun et al [42]	97	88	94	95
Mowatt et al [43]	99	89	93	100
Stein et al [44]	98	88	93	96

N/A = not applicable; NPV = negative predictive value; PPV = positive predictive value.

values are high for 16- and 64-detector technology for both per-patient and per-segment analyses.

Beyond current 64-detector technology. At the time of this writing, a new generation of CT scanners are being released. Equipment manufacturers are taking diverse paths with regards to advancing the technology. It is likely that these advancements will improve on the current 64-detector technology. There is insufficient literature concerning these new technologies to be included in this article.

Disease Prevalence and Pretest Cardiovascular Risk

The vast majority of studies included in the available meta-analyses are in patient groups with a high prevalence of coronary artery disease (mean prevalence of coronary disease, 59% [26], 53% [42], and 61% [44]). Disease prevalence has a bearing on the negative and positive predictive values of an investigation. High disease prevalence results in higher positive predictive values and lower negative predictive values, low prevalence results in lower positive predictive values and higher negative predictive values [45,46]. Furthermore, although Bayesian theory dictates that the sensitivity or specificity of an investigation is not affected by disease prevalence, they are influenced by the composition of the population on which an investigation is assessed [47,48]. In the context of CCTA, in a population with a low or intermediate likelihood of coronary disease, not only is the prevalence of coronary disease low, but it is to be expected that the severity of the disease will be less than in a high-risk group, with different lesion composition and disease distribution within the coronary tree. The sensitivity and specificity of CCTA in the low- and intermediate-risk groups therefore may be different from that in the published meta-analyses.

Two studies have assessed the performance of CCTA in different patient groups. Husmann et al [48] stratified 88 patients into high-, intermediate-, and low-risk groups according to Framingham 10-year risk. Meijboom et al [49] stratified 254 patients into high-, intermediate-, and low-risk groups according to the Duke Clinical Score. Both studies found similar results. Specificity was lower in the high-risk group. Positive predictive value was lower in the low-risk group. Negative predictive value was high across all groups in per-patient and per-segment analyses. The implication of these findings is that in low- and intermediate-risk groups, CCTA can exclude disease reliably, but there will be an increasing number of false-positive cases as pretest risk decreases.

Patient Parameters Influencing CCTA Diagnostic Performance

Certain patient parameters have been shown to affect the diagnostic performance of 64-slice CCTA adversely: coronary calcification, high heart rate, heart rate variability, and body mass index.

Higher levels of coronary calcification are associated with poorer 64-detector CCTA diagnostic performance, with various investigators showing an increased number of unassessable segments, lower specificity, lower positive predictive value, and poorer image quality [32,33,50−52]. The widely accepted explanation for this is that calcification causes blooming artifact and beam-hardening artifact, which lead to an overestimation of the degree of stenosis. This effect is more pronounced when calcification is denser, however, there is great heterogeneity among the studies in determining high- and low-calcification categories and there is no consensus as to an unacceptably high level for the performance of CCTA.

High heart rates are associated with poorer diagnostic performance of 64-detector CCTA [33,51−55] as a result of motion artifact. In the majority of published articles, β-blocking medication was used to limit the heart rate. It should be noted that the target heart rate was variable (most commonly <65 bpm) and not always achieved, but that in general, image quality improves as the heart rate is lower.

Variability of heart rate is associated with poorer diagnostic performance [55,56] as well, owing to data misregistration artifact between heart beats. β-blockade is beneficial in reducing heart rate variability [55].

Obesity causes increased image noise, which reduces contrast resolution of the coronary arteries [51]. Raff et al [33] reported decreased sensitivity, specificity, positive predictive value, and negative predictive value in 64-detector CCTA in patients with a body mass index greater than 30 kg/m^2.

Multicentre Evidence

The vast body of evidence on the performance of 64-detector CCTA is based on single-centre academic unit publications. Ong et al [41] reported findings from a centre with no prior experience in CCTA and showed very high negative predictive values but poorer per-patient sensitivity and positive predictive values, and a higher percentage of unevaluable segments than those published by more experienced centres. They concluded that inexperienced centres may not be able to replicate the published experienced centre results.

At the time of this writing, the ACCURACY trial [52] is the only published multicentre trial assessing the performance of 64-detector CCTA. A total of 240 low- to intermediate-risk patients were recruited and had 64-detector CT and coronary angiography performed at 16 different centres, 83% of the patients being recruited and scanned at nonacademic centres. CCTA studies were not read at the recruiting centre, but were read by 2 of 3 investigators, one of whom was from a nonacademic centre. Per-patient analysis for coronary artery stenoses of 50% or greater showed a sensitivity of 95%, a specificity of 83%, a positive predictive value of 64%, and a negative predictive value of 99%. Similar to all the published single-centre trials, negative predictive value was high, however, sensitivity was slightly lower and positive predictive value was considerably lower. Whether this is because of the multicentre nature of the study or the relatively low prevalence of disease in the study population (25%) is unclear, however, the positive predictive value is similar to that reported in studies assessing the performance of 64-detector CCTA in high- versus low-risk populations [48,49].

Summary

1. Sixty-four–detector CCTA outperforms 16-detector CCTA, which in turn outperforms 4-detector CCTA. The major difference is in the number of unassessable studies and unassessable vessel segments.
2. Sixty-four–detector CCTA detects coronary stenoses of 50% or greater with a high sensitivity and high negative predictive value.
3. Positive predictive value is lower in populations with low disease prevalence.
4. Coronary calcification, high heart rate, variable heart rate, and obesity have a negative impact on the diagnostic performance of 64-detector CCTA.
5. Results of inexperienced centres may not replicate those published by experienced academic centres.

Functional Relevance, Lesion Quantification, and Characterization

It should be recognized that CCTA assesses the anatomy of the coronary tree and does not provide information as to the functional relevance of stenoses. Comparison of conventional coronary angiography with stress-perfusion positron emission tomography has shown that the vasodilator reserve (the ability to increase flow from baseline resting state) declines incrementally between 40% diameter stenosis up to 80% diameter stenosis [57]. Almost all of the studies of 64-detector CCTA have used the figure of 50% to represent a significant stenosis. When the functional relevance of these significant stenoses is assessed, a large proportion is found not to be associated with stress-induced ischemia. Meijboom et al [58] found only 18% of CCTA stenoses of 50% or greater to have a fractional flow reserve of less than 0.75, the level indicative of stress-induced ischemia. In comparing 64-slice CCTA with single photon emission CT myocardial perfusion imaging, Gaemperli et al [59] showed a CCTA stenosis of 50% or greater to have only a 58% positive predictive value of positive myocardial perfusion imaging, Schuijf et al [60] showed only 39% of patients with stenosis of 50% or greater to have abnormal myocardial perfusion imaging, and Scholte et al [61] showed 67% of patients with stenosis of 50% or greater to have abnormal myocardial perfusion imaging.

A small number of studies have compared 64-slice CCTA with conventional angiography for detection of stenoses greater than 50%. Herzog et al [62] reported similar sensitivity, specificity, positive predictive value, and negative predictive value for 50% and 70% lesions, with a negative predictive value of 100% for patient-based analysis. Budoff et al [52] also reported very similar sensitivity, specificity, and negative predictive value (99%) for 50% and 70% stenoses, however, positive predictive value was lower for 70% lesions. Muhlenbruch et al [39] reported only on 70% lesions and showed a sensitivity of 98%, a specificity of 50%, a positive predictive value of 94%, and a negative predictive value of 75%. In this study, prevalence of disease was 90%, which may explain the low negative predictive value and low specificity. Studies comparing 64-slice CCTA with conventional angiography that have categorized lesions further into quartile or smaller ranges of stenoses have shown a tendency for CTA to overestimate the degree of stenosis [63–65]. Raff et al [33] determined that although the mean difference between CCTA and conventional angiography grading of stenoses was small (1.3%), the standard deviation of differences was such that in only approximately 90% of cases, the CCTA grading was within ± one quartile grading of the conventional angiogram.

Intravascular ultrasound (IVUS) is used commonly in the catheterization laboratory to give more anatomic information and more accurate quantification of stenotic coronary plaques [66]. Similar to IVUS, CCTA shows not only the vessel lumen but also plaque and vessel wall. Several investigators have compared 64-detector CCTA with IVUS for the detection and quantification of disease. Sun et al [67] reported excellent results for the detection of plaque in a population with suspected coronary disease (sensitivity, 97%; specificity, 90%; positive predictive value, 90%; and negative predictive value, 97%). In a population with less disease, Gregory et al [68] reported poorer results for plaque detection (sensitivity, 70%; specificity, 92%; positive predictive value, 89%; and negative predictive value, 77%). Several investigators reported reasonable correlation between CCTA and IVUS for lesion quantification. For percentage area of stenosis Sato et al [69] reported a correlation coefficient of 0.87 and Leber et al [30] reported a correlation coefficient of 0.61. Both commented that CCTA tends to underestimate the percentage of stenosis owing to an overestimate of the lumen size. Caussin et al [70] reported a correlation coefficient of 0.88 for the assessment of mean luminal area. For the assessment of lesion plaque volume Leber et al [71] reported a correlation coefficient of 0.69 and Otsuka et al [72] reported a correlation coefficient of 0.98. In all of these studies, selected arteries or segments were used for the IVUS study and by the nature of the IVUS procedure, these assessments generally were made on larger proximal vessels.

Plaque characterization is an area of great interest. Several studies have reported 64-slice CCTA demonstration of certain characteristics that are more common in culprit

Table 3
Sixty-four−detector CCTA studies of coronary in-stent stenosis (per stent analysis)

	Stents	Excluded	Stenoses	Sensitivity	Specificity	PPV	NPV
Hecht et al [81]	132	0	17	94	74	39	99
Carrabba et al [82]	87	0	13	84	97	92	97
Carbone et al [83]	88	21	16	75	86	71	89
Das et al [84]	110	13	32	97	88	78	91
Schuijf et al [85]	76	11	6	100	100	100	100
Oncel et al [86]	39	0	19	89	95	94	90
Rixe et al [87]	102	43	12	88	98	86	98
Cademartiri et al [88]	192	14	20	95	93	63	99
Ehara et al [89]	125	15	24	91	93	77	98
Rist et al [90]	46	1	8	75	89	67	94

NPV = negative predictive value; PPV = positive predictive value.

lesions in patients with acute coronary syndrome such as positive remodelling, low attenuation plaque, spotty calcifications, and ring-like foci [73−77]. Results for characterization of plaque composition, however, are disappointing in that although CCTA is excellent at differentiating calcified and noncalcified plaque, differentiation between the different components of noncalcified plaque (fibrous, fibrofatty, necrotic) is poor [67,78].

Summary

1. A significant percentage of coronary stenoses of 50% or greater are not associated with ischemia.
2. There are little data regarding CCTA versus conventional angiographic quantification of lesions other than binary quantification around 50% stenosis. The data available indicate that there is considerable variability in quantification, however, the tendency is for CCTA to overestimate lesions. Systematic overestimation of the degree of stenosis would maintain a high sensitivity and negative predictive value at the expense of specificity and positive predictive value.
3. On the basis of limited data, CCTA compares favourably with IVUS for detection of plaque in a population with high disease prevalence, but compares less favourably when disease is less prevalent.
4. CCTA quantification of disease compares favourably with IVUS but tends to underestimate the degree of stenosis.
5. CCTA performs well in the differentiation of calcified and noncalcified plaques, but poorly between different types of noncalcified plaques.

Assessment of Coronary Stents

Early evidence for 64-detector CCTA visualization of coronary stents was discouraging. Maintz et al [79] assessed the lumen visibility of 68 different coronary stents in an ex vivo static model and reported only 10 of the stents to allow greater than 66% lumen visibility. Stent diameters ranged from 2.5 to 4 mm (majority, 3 mm). In vivo, Sheth et al [80] reported 56% of 54 stents scanned within 48 hours of deployment to be unassessable owing to artifact.

Despite these shortcomings, a number of investigators subsequently have shown 64-detector CCTA to have a reasonably high negative predictive value for detection of in-stent stenosis ranging from 89% to 100% (Table 3) [81−90]. The literature shows a reasonably high but variable sensitivity (75%−100%) and specificity (74%−100%) and a wide range of positive predictive values (39%−100%). Also variable was the percentage of stents regarded as unassessable (range, 0%−42%). Pooled data from these studies showed 11.8% of stents to be unassessable and to have been excluded from analysis. The results are summarized in Table 3. Factors influencing lumen visibility and stent assessability were stent diameter, stent material, stent strut size and density, overlapping stents, heart rate, and body mass index [79,85,87,91,92]. In particular, assessability was poor for stents of 3 mm or less in diameter [80,83,87].

Summary

1. A significant percentage of coronary stents prove to be unassessable by 64-detector CCTA.
2. Adverse features for stent assessment are small size (<3 mm), dense stents with large struts, overlapping stents, high heart rate, heart rate variability, and high body mass index.
3. Excluding unassessable stents, 64-detector CCTA has a high negative predictive value for detection of in-stent stenosis of 50% or greater.

Assessment of Coronary Artery Bypass Grafts

Coronary artery bypass grafts are less mobile, contain less calcification, and in the case of vein grafts are larger than the coronary arteries and so should be well suited for assessment with 64-detector CCTA. Multiple investigators have addressed this and have reported similar results, despite differences in graft types (arterial or venous) and different study exclusion criteria with regards to high heart rate or arrythmia [93−100]. The results are summarized in Table 4.

Similar to CCTA of the native coronary arteries, CCTA of coronary artery bypass grafts has extremely high sensitivity and negative predictive value, close to 100%. Specificity and positive predictive value are also very high, but slightly less impressive. In all studies differentiating occlusion from

Table 4
Sixty-four–detector CCTA studies of coronary artery bypass graft stenosis (per-graft analysis for combined stenosis of 50% or greater and occlusion)

	Grafts (A/V)	Unassessable	Stenoses	Sensitivity	Specificity	PPV	NPV
Malagutti et al [93]	109 (45/64)	0	49	100	98	98	100
Pache et al [94]	96 (23/73)	3	45	98	89	90	98
Dikkers et al [95]	69 (52/17)	4	17	100	99	94	100
Ropers et al [96]	138 (37/101)	0	54	100	94	92	100
Meyer et al [97]	406 (147/259)	9	116	97	97	93	99
Jabara et al [98]	147 (47/100)	20	42	95	100	100	98
Onuma et al [99]	146 (74/72)	8	10	97	98	94	99
Feuchtner et al [100]	70 (46/24)	0	14	85	95	80	96

A/V = arterial/venous; NPV = negative predictive value; PPV = positive predictive value.

stenosis, performance was better for occlusion than for stenosis. The small numbers of errors (nearly all false positives) and unassessable grafts were caused almost exclusively by metallic clips adjacent to the graft, most often at the distal anastomosis, and these were more common in arterial grafts. The size of the graft target vessel, [100] heart rate, and arrythmia [97] are other factors that influence diagnostic accuracy. In 2 of the studies, grafts were depicted at CCTA that were not visualized at conventional angiography.

In clinical practice the status of the native nongrafted coronaries and the grafted run-off vessels is essential information for decisions on revascularization. In this patient group, the native coronaries, and in particular the graft run-off vessels, have a higher likelihood of being small, diseased, and calcified and so are relatively unfavourable for CCTA assessment. This is confirmed by those studies reporting assessment of the native coronary arteries and run-off vessels showing significantly poorer performance than the body of literature for assessment of coronary disease in nongrafted patients [93,95,96,99].

Summary

1. Sixty-four–detector CCTA has excellent negative predictive value and very good positive predictive value for detection of coronary artery bypass graft stenosis of 50% or greater.
2. A small percentage of grafts are unassessable by 64-detector CCTA.
3. Adverse features for graft assessment are adjacent metallic clips, arterial grafts, small target vessels, high heart rate, and heart rate variability.
4. Sixty-four–detector CCTA determination of the status of the run-off vessels and native coronary arteries is relatively poor.

Imaging of Coronary Anomalies

Although coronary anomalies are relatively rare conditions, a small proportion have the potential to cause ischemia, myocardial infarction, and sudden death [101]. In young athletes, coronary artery anomalies are the second most common cause of sudden death as a result of structural heart disease [102]. The identification of the origin and course of aberrant coronary arteries by conventional angiography can be difficult [103]. Because of the 3-dimensional nature of the data set, CCTA is very well suited to detect and define the anatomic course of coronary artery anomalies and their relationship to other cardiac and noncardiac structures. A number of case reports and several research reports [104–107] have shown that the CCTA analysis of coronary anatomy in these patients is straightforward and very reliable, with accuracy close to 100%.

Noncoronary Cardiac Imaging

Ventricular Function

Left ventricular function

By using advanced postprocessing methods, left ventricular functional parameters such as end-diastolic and end-systolic volumes, stroke volume, ejection fraction, myocardial mass, and regional wall motion abnormalities can be assessed and have shown good agreement with echocardiography, monoplane and biplane ventriculography, and gated single photon emission CT as well as magnetic resonance imaging (MRI) [108–120]. A recent meta-analysis of MDCT left ventricular function analysis compared with MRI in 252 patients showed a weighted average difference of -1.7% ± 3.1%, a difference that is not relevant in clinical practice [121].

Right ventricular function

There are limited data on the accuracy of MDCT in assessing right ventricular function. Right ventricular (RV) quantification requires optimized contrast opacification of the right ventricle. Small studies, mostly using 16-detector CT, have shown good correlation of RV ejection fraction, RV end-diastolic volume, RV end-systolic volume, and stroke volume with radionuclide ventriculography, MRI, cardiac catheterization, and echocardiography in patients suspected of coronary artery disease, [116,122,123] suspected RV dysfunction [124,125], suspected pulmonary emboli [126,127], and congenital heart disease [128].

Valvular Function

The assessment of aortic stenosis has been the subject of several studies using 16-, 40-, and 64-detector CT. Aortic valve area using planimetry has been compared with transthoracic echocardiography (TTE) using the Doppler continuity equation, cine MR planimetry, and transesophageal echo planimetry in patients with and without aortic stenosis. All studies showed good correlation between CT and the other modalities ($r = 0.76$–0.99) [92,129–134]. Some investigators found a slight systematic overestimation of aortic valve area compared with TTE [132,133]. Only 2 investigators evaluated the sensitivity and specificity of 64-detector CT in the detection of aortic stenosis with sensitivities ranging between 82% and 100% and specificities ranging between 77% and 93.7% [129,133]. In his study of 52 patients with aortic stenosis evaluated with 64-detector CT, Habis [133] also found good interobserver agreement (difference, 0.002; variability, 0.112 cm^2).

Fewer data exist concerning the use of CT in the evaluation of aortic regurgitation. All studies showed good correlation of aortic regurgitant area with the severity of aortic valve regurgitation on TTE ($r = 0.75$–0.86) [135–137]. Feuchtner [135] found good interobserver agreement ($r = 0.97$) for the determination of the aortic regurgitant area. However, both Feuchtner et al [135] and Jassal et al [136] found a low negative predictive value, especially in patients with mild aortic regurgitation, possibly owing to artifact caused by the presence of aortic valve calcification.

Finally, with regards to mitral valvular disease, only one study could be found comparing 16-detector CT with TEE and catheter ventriculography in 19 patients with mitral regurgitation. CT planimetry of the mitral valve regurgitant orifice correlated significantly with the other modalities [138].

Myocardial Perfusion and Viability

Although the pharmacokinetics of CT contrast agents will allow first-pass perfusion imaging, and assessment of delayed enhancement for myocardial viability, only preliminary studies are available showing good agreement with MR [109,139–146]. The radiation dose required to perform these studies remains a concern.

Left Atrium and Pulmonary Vein Assessment

It has been shown that the pulmonary veins are the source of triggers initiating atrial fibrillation in 90% to 96% of patients and that these foci can be eliminated effectively using catheter ablation [147]. Success rates in patients without underlying structural heart disease are greater than 80% [148]. Different ablation techniques include ostial segmental isolation of the pulmonary vein [149] and anatomically based circumferential ablation [150]. Preprocedural knowledge of the left atrial and pulmonary vein anatomy is crucial for the electrophysiologist and this can be provided with multidetector CT. Four-detector and higher scanners can characterize posterior left atrial and pulmonary vein anatomy accurately without and with ECG gating [151]. Sixteen- and 64-detector CT offer the advantage of decreased scan time, decreased cardiac motion, and isotropic data sets, which improve image quality even without gating. Important information concerning the number, size, distance from the ostium to the first branch, and the presence of anatomic variants of pulmonary veins are important to help select the size of the ablation catheters used to perform the procedure. The dimensions of the left atrium, the presence of left atrial appendage thrombus, and the anatomic course of the esophagus relative to the posterior left atrial wall and pulmonary veins also can be assessed [152,153].

Image integration systems for catheter ablation procedures now are being used. With this technology, the 3-dimensional CT reconstructions are merged with the electroanatomic mapping data at the time of the procedure, with an accuracy of 2-mm distance between corresponding points on the 2 images [154]. Some investigators have found an increased success rate for catheter ablation using this technique [155,156]. Kistler et al [155] also found a decrease in fluoroscopy time.

Finally, MDCT has proven to be useful in the follow-up evaluation of patients after ablation therapy to assess for the development of complications, especially to monitor the development of pulmonary vein stenosis [157,158].

Coronary Vein Anatomy

In cardiac resynchronization therapy, left ventricular (LV) pacing is achieved by positioning the LV lead in one of the tributaries of the coronary sinus. Although the success rate for transvenous LV lead placement is relatively high, in 5% to 12% of patients the procedure does not succeed, [159] and these numbers may be even higher in inexperienced centres. Failure of LV lead placement has been attributed to the inability to insert catheters in the coronary sinus and the lack of suitable side branches [159,160]. Knowledge of the cardiac venous anatomy before these procedures may facilitate LV lead positioning. In 2005, Jongbloed [161] et al showed that noninvasive visualization of the coronary venous anatomy was feasible with 16-detector CT and Van de Veire et al [162] showed that visualization of the major tributaries of the coronary sinus was comparable between invasive venography and MDCT venography. He also suggested that an additional 2-second delay should be applied after the contrast bolus reached the descending aorta before triggering the scan would optimize the scan for venous visualization.

Congenital Heart Disease

The population of adults with congenital heart disease is increasing rapidly as a result of improved outcomes of surgical and catheter-based treatment strategies. The most obvious and clear indication for CCTA selection over MR in imaging these patients is the presence of a permanent implanted pacemaker or automated implantable cardiac defibrillator. CCT should act to augment the data collected using echocardiography, particularly when there are limitations to the echocardiographic examination owing to poor acoustic windows in the setting of prior cardiac surgery or chest wall deformity [163]. CT also supplements echocardiography data in areas of echocardiographic weakness, particularly in the evaluation of the aortic arch, coronary arteries, branch pulmonary arteries, and collateral vessels. The decision to use

CCTA should be based on the question to be answered at hand [164]. CT strengths in congenital heart disease include but are not limited to its fast acquisition time, limiting the need for sedation. Its inherent high-spatial resolution offers evaluation of cardiac chamber size, conduits, baffles, aortic arch, great vessels, and pulmonary arteries and veins [165].

Pericardial Disease and Cardiac Masses

Echocardiography is the modality of choice in the initial investigation of pericardial disease and cardiac masses. It provides high-resolution, real-time images with recently improved tissue characterization using tissue harmonics and contrast echo [166]. However, because of restricted imaging windows and limited tissue characterization, CT and MR play an important role in the evaluation of pericardial thickening and cardiac masses. CT is superior to MR in the detection of calcification and to evaluate the extracardiac extent of disease such as involvement of the lungs. CT also is faster and less operator dependent than either echo or MR. MR has much better soft-tissue contrast and enhancement characteristics of masses can be assessed without the use of ionizing radiation. In addition, the physiologic effects of pericardial abnormalities on the cardiac chambers are better characterized with MR as compared with CT because of its higher temporal resolution [167–169].

Extracardiac Findings

As compared with echocardiography, nuclear imaging, and conventional coronary angiography, CCT is unique in its ability to image not only the heart, but also the surrounding mediastinum, pulmonary vasculature, lungs, chest wall, and upper abdomen. Extracardiac findings are found quite commonly on CCT examinations. Multiple investigators have reported on the incidence and significance of these findings on cardiac CTA and electron-beam CT for calcium scoring. Although the definition of significant findings varied between studies, 4.2% to 22.7% of patients were reported to have findings that required additional investigations or immediate intervention [170–178]. Haller et al [172] showed that only 35.5% of the total chest volume was displayed on dedicated coronary artery MDCT focused on the heart, whereas 70.3% of the chest was visible when coronary artery MDCT raw data were reconstructed with the maximal field of view.

Discussion

Based on the literature review and consensus expert opinion, guidelines and standards for the performance of CCT are provided later.

Guidelines for the Performance of CCT

Calcium score

The Writing Group supports the use of calcium scoring in asymptomatic patients with an intermediate risk of cardiovascular events using a traditional scoring system because this may influence the decision to intensify risk factor modification.

The Writing Group does not support calcium scoring in the following situations: (1) in asymptomatic patients at low or high risk for cardiovascular events, or (2) to monitor CAC progression over time.

Coronary artery imaging

Coronary CTA should be performed only in centres with adequate equipment by adequately trained staff. Studies must be supervised and interpreted by adequately trained physicians (see Standards for the Performance of Cardiac CT section). Studies should be performed only on patients in whom a diagnostic quality study is likely to be obtained and in whom the result of the study will influence patient management.

Coronary Artery Evaluation: Clinically Stable Patients

The Writing Group supports the use of coronary CTA in:

1. Symptomatic patients with low to intermediate pretest probability of obstructive coronary artery disease who otherwise would be considered for conventional coronary angiography. This typically would be patients with chest pain and an equivocal or uninterpretable stress test.
2. Patients at low to intermediate risk of coronary artery disease with planned surgery for valvular or structural heart disease who otherwise would require preoperative conventional coronary angiography.

The Writing Group does not support the use of coronary CTA in:

1. Symptomatic patients with high pretest probability of obstructive coronary artery disease or previously documented coronary artery disease.
2. Asymptomatic patients. It should be emphasized that there currently is no evidence to support the use of coronary CTA as a screening examination for coronary artery disease.

Coronary Artery Evaluation: Clinically Unstable Patients

The use of coronary CTA in acute chest pain is controversial. The high negative predictive value of coronary CTA is a valuable tool, but the relatively poorer positive predictive value, particularly in populations with a low disease prevalence, is a potentially problematic source of false-positive studies. Furthermore, there is relatively poor correlation between CTA-detected obstructive lesions and myocardial ischemia. Therefore, positive studies require further assessment with either stress testing and/or conventional coronary angiography.

The Writing Group advocates the use of coronary CTA in patients with acute chest pain only in collaboration with experienced clinicians for patients with low to intermediate pretest probability of coronary artery disease.

The Writing Group does not support the use of coronary CTA in patients with acute chest pain who have either a high pretest probability of obstructive coronary artery disease or ECG or cardiac enzyme evidence of acute coronary syndrome.

Coronary Stent Evaluation

The Writing Group does not support the routine use of coronary CTA for the evaluation of coronary artery stent patency.

The Writing Group supports the use of coronary CTA for the evaluation of coronary stent patency only in collaboration with experienced physicians in select cases with low to intermediate probability of stent stenosis who otherwise would have conventional coronary angiography. Stents should have a diameter greater than 3 mm. It is advised that all unassessable and positive cases have conventional angiographic confirmation of stent status.

Coronary Artery Bypass Graft Evaluation

The Writing Group supports the use of coronary CTA for coronary artery bypass graft evaluation only in collaboration with experienced clinicians in patients in whom the clinical question is restricted to graft patency. The relatively poor performance for assessment of run-off vessels in these patients is likely to impede management decisions regarding revascularisation.

Coronary Artery Anomaly Evaluation

The Writing Group supports the use of coronary CTA for the evaluation of suspected clinically relevant coronary anomalies.

Noncoronary cardiac imaging

Ventricular function. The Writing Group supports the use of CCT in the assessment of ventricular function when (1) a retrospectively gated examination is obtained for other accepted clinical indications, or (2) if this information cannot be obtained through the use of other imaging modalities that do not require the use of ionizing radiation such as echocardiography or MRI.

Valvular function. The Writing Group supports the use of CCT in the assessment of valvular function when (1) a retrospectively gated examination is obtained for other accepted clinical indications, or (2) if this information cannot be obtained through the use of other imaging modalities that do not require the use of ionizing radiation such as echocardiography or MRI.

Myocardial Perfusion and Viability

Because of the limited data to date, the Writing Group does not support the routine use of CT for assessing myocardial perfusion and viability unless this is part of a research study.

Left Atrium and Pulmonary Vein Assessment

The Writing Group supports the use of either gated or ungated CCT for the assessment of the left atrium and pulmonary veins (1) before atrial fibrillation ablation, and (2) to assess suspected postprocedural complications.

Coronary Vein Anatomy

The Working Group supports the use of CCT for the preprocedural assessment of the coronary veins in consultation with an electrophysiologist to answer a specific question that will affect the management of an individual patient.

Congenital Heart Disease

The Writing Group advocates a team approach of specialists with interest and knowledge in pediatric and adult congenital heart disease, including clinical and interventional cardiologists, radiologists, and echocardiographers. As with any new technology and diagnostic technique several questions should be asked before selection of CT as the imaging test of choice over more well-established techniques such as MRI and echo.

1. Does CCT have the ability to answer the clinical question?
2. Will the results affect clinical management to justify the ionizing radiation exposure?
3. Can another test without ionizing radiation answer the clinical question without greater difficulty?
4. Is ECG gating necessary and, if so, can dose-reduction strategies such as prospective gating be used to lower exposure?

Although there are no established criteria for patient selection, the Writing Group advocates a balanced and thoughtful approach to CCT in congenital heart disease as outlined earlier.

Pericardial Disease and Cardiac Masses

The Writing Group supports the use of CCT in the investigation of pericardial disease or cardiac masses when:

1. The findings on echo or MRI are inconclusive.
2. There is a contraindication to MRI such as the presence of a pacemaker, claustrophobia, or the inability to tolerate the examination.
3. CT is required to complete the staging of a probable cardiac malignancy.

Extracardiac Findings

Investigators have determined that only one third of the total chest volume is displayed on the coned down field of view images of a CCT, but the relatively high radiation dose acquisition contains information on the entire thorax in the range of z-axis covered.

Because of this, the Writing Group firmly believes that it would be unethical to exclude these structures from interpretation and therefore a second reconstruction of the images on mediastinal and lung windows at full field of view to allow the same breadth of visualisation as a regular chest CT should be performed routinely in every case. These images should be reviewed by a radiologist to provide the opportunity for an alternative diagnosis that may account for the patient's symptoms or detect important but clinically occult problems such as early stage lung cancer.

Standards for the Performance of CCT

CT facility requirements

For diagnostic-quality CCT, a CT scanner should meet or exceed the following specifications:

1. For contrast-enhanced CCTA a scanner must be capable of achieving in-plane resolution of less than 0.5 × 0.5 mm axial, z-axis spatial resolution of less than 1 mm longitudinal, and temporal resolution of less than 0.25 seconds.
2. Tube heat capacity that allows for a single acquisition greater than 20 seconds.
3. All active CT facilities must have dose-reduction strategies in place. This should include but not be limited to ECG dose modulation and specific protocols for smaller patients. Ideally, laboratories also should have the ability to acquire data with prospective gating or step-and-shoot sequential axial scanning.
4. Minimum section thickness no greater than 3 mm for calcium score CT and no greater than 1.5 mm for CT angiography [179].

To allow for adequate contrast-enhanced CCT, a power injector capable of delivering a programed volume of a contrast agent at a steady flow rate of at least 4 mL/s for a delivery of greater than 300 mg/mL of iodine is necessary. The precise optimal concentration of the contrast to be used is controversial. A dual-chambered power injector is a requirement for adequate coronary artery visualization and for other noncoronary CT applications [180].

Workstation capabilities must allow the interpreting physician to perform all of the necessary postprocessing and data manipulation to ensure a thorough interpretation. These should include, but not be limited to, multiplanar reformats, advanced vessel analysis, and volume rendering.

Patient preparation

Because CCTA should not be performed in patients with an irregular heart beat such as atrial fibrillation, an ECG should be available or obtained before the scan. Contrast injection rates will vary between 4 and 8 mL/s, and therefore patients should have an 18-gauge catheter or larger inserted, preferably in a cubital vein. Because most CCTA examinations will be performed on 64-detector CT scanners, heart rate control is imperative to obtain diagnostic-quality examinations and to reduce radiation dose. A heart rate of 65 beats or less per minute is desirable for all patients. Physicians should be familiar with the dosage and administration of oral and intravenous β-blockers and calcium channel blockers as well as with contraindications to their use and their side effects. Physicians also should be familiar with the treatment of adverse reactions to these medications.

All patients undergoing CCT ideally should receive oral nitrates immediately before image acquisition. Physicians should be aware of the contraindications to their use and the treatment of adverse reactions if they occur [2,181].

Radiation control

As in all imaging, care always must be taken to ensure the patient receives the lowest radiation dose possible. The policy of As Low As Reasonably Acceptable (ALARA) must be at the very heart of any coronary CT facility. The director or interpreting physician must be familiar with all of the recent dose-reduction strategies [182, 183]. Prospective gating, or so-called *step-and-shoot axial scanning*, should be considered when it could answer the clinical question adequately. The decision to use such techniques should be made with an understanding of its limitations such as the lack of functional data and the inability to scan patients with significant variability in heart rate. Other steps to limit patient dose including the use of breast shields, individualized kVp selection, and limits on z-axis coverage should be implemented [184]. Substantial dose savings can and should be realized by lowering the tube voltage from the routine 120 kV to 100 kV or 80 kV [185]. This also results in increases in the level of vascular attenuation. Pooled experience would suggest that in patients with a body mass index less than 25 that 100 kV can be used routinely with more than satisfactory results. Similarly, low kV scanning should be used when performing CCT in adolescent and pediatric patients for suspicion of coronary anomalies and other congenital cardiovascular conditions [186]. Dose modulation should be used routinely, except when planning on evaluating valve disease in systole, which should be undertaken when other techniques already have been considered.

Reporting standards

Structured and complete reporting are key elements for a functioning and valuable service in all areas of medical imaging. Never is this truer than in coronary CT angiography. Although formal reporting standards are not being proposed, there are a number of recommendations that should be considered.

1. Patient data: demographics, indications, diagnosis, background data (Framingham risk assessment), relevant clinical history, and consent.
2. Technical data: medications administered for rate control and coronary dilatation, acquisition parameters, reconstruction techniques, vitals, and complications. The technical component of the report should refer to the type

of gating used for the study. It also should refer to the contrast material used, both the type and volume.

3. Results: The first statement in the results component of a report should refer to the quality of the study. This includes an overview statement and some explanation for limitations or artifacts that were encountered. After the technical quality of the study is stated, the report should consist of a formal evaluation of noncardiac, cardiac but noncoronary, and coronary findings.

Noncoronary cardiac findings should include a review of the great vessels, myocardium, cardiac chambers, pericardium, and valvular disease. Data regarding function and valve assessment would be limited to helical retrospective acquisitions.

Coronary assessment should include but not be limited to a review of dominance including a descriptor of course and branching patterns. There also should be an overview statement regarding the presence or absence of plaque burden and the type of plaque. For the reporting of stenosis, use of the American Heart Association classification is recommended but is not believed to be a requirement [185]. Consistent and accurate vessel labeling and description is of utmost importance. Common terminology used in conventional angiography reports describing lesions as proximal, mid, and distal according to the main coronary and branch anatomy should be used. Vessel size and distribution of various coronary segments is important to help guide clinical decision making. In addition, Agatston or mass calcium scores should be reported when formal calcium scanning is undertaken.

Stenosis evaluation and visual quantification should be performed in all coronary CT angiograms when plaque is present. Although the strength of coronary CT angiography is in the exclusion of disease in patients with low pretest probability [49,52], attempts should be made to quantify stenosis, understanding the limitations of stenosis grading in CT caused by limitations in spatial resolution. Quantitative CCTA is not required but a consistent grading scale should be used. A quartile system or a 5-point grading scale [187] is recommended to help guide the referring physician regarding the need for further noninvasive testing or invasive angiography. Stenosis descriptors also should include comments regarding vascular remodelling and plaque density when possible. All CT angiography facilities should pursue conventional angiographic follow-up evaluation when available to assess internal accuracy.

Training and continuing medical education requirements

The training and continuing medical education requirements for the performance of CCT are difficult and controversial issues. Because CCT currently is being performed by both radiologists and cardiologists, it is important that adequate training take place in both subspecialties. It also is important that both subspecialties work in a collaborative environment. For these reasons, the Canadian Association of Radiologists and the Canadian Cardiovascular Society are exploring the possibility of developing training standards for radiologists and cardiologists that would be acceptable to both societies as part of a larger collaborative document on CCT. The training requirements will apply to a scope of CCT practice that includes the contrast-enhanced evaluation of cardiac chambers, coronary vessels and coronary bypass grafts, and the nonenhanced evaluation of coronary calcium. These requirements will not include approval necessary for other vascular or thoracic imaging.

Conclusions

CCT allows a rapid noninvasive assessment of cardiac anatomy and function. Radiologists must play a crucial role in the education of physicians referring patients for CCT and in the proper implementation of a CCT program within their own institutions. The Canadian Association of Radiologists recognizes the importance of setting appropriate standards and guidelines for this rapidly evolving imaging technique.

Acknowledgements

The authors gratefully acknowledge the editorial comments provided to us by the Canadian Cardiovascular Society during the development of this article. The authors have incorporated their valued suggestions.

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